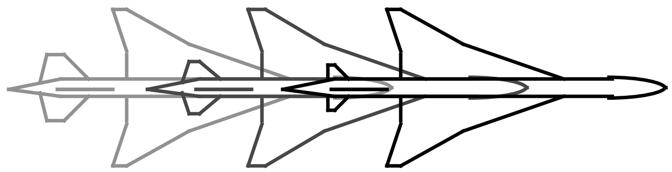
Control System Requirements for Multidisciplinary Design Applications

Final Project Review NAG-1-1573
August 1997



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Topics

- Project Motivation and Objectives
- Aerodynamic Estimation
- Control System Risk Assessment
- Design Studies
- Significant Contributions
- Technology Transfer Efforts

Project Motivation

Preliminary design sophistication has increased significantly since the 1930's.

'30 - '50

Airframe/Propulsion

Payload

Performance

'50 - '60

Airframe/Propulsion

Avionics/Payload

RDT& E Cost

Performance & Effectiveness

'60 - '70

Airframe/Propulsion

Avionics/Payload

Support/Cost

Performance/Cost /Effectiveness

43rd AGARD Flight Mechanics Panel Meeting, Oct. 1973

'70 - '90

Significant increases in SUBSYTEM performance

- digital control
- composites
- new aero controls

Where did cost go?

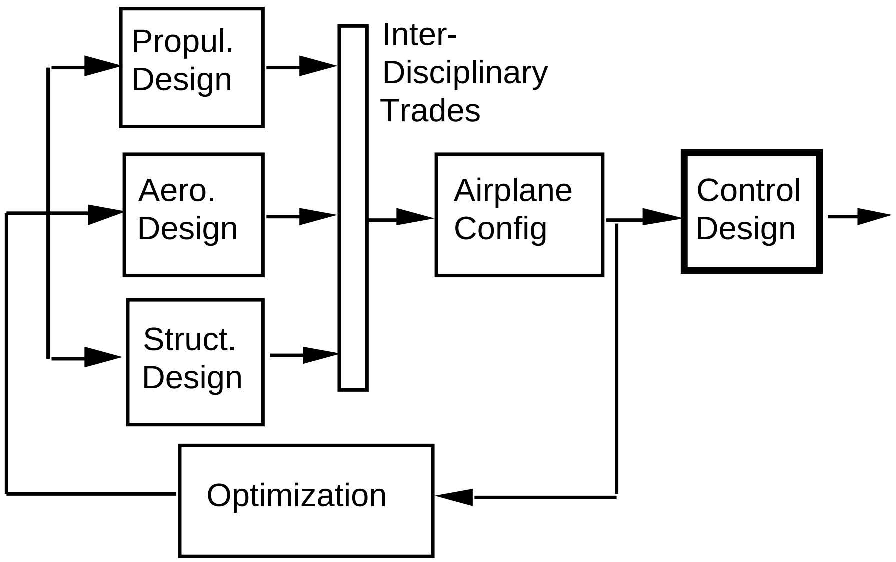
'90 ---

Increases in TOTAL aircraft performance?

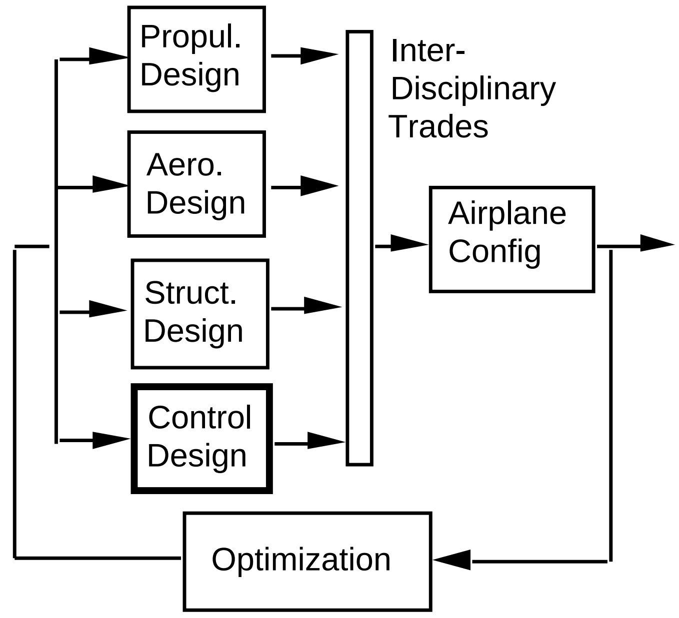
Cost/Cost/Cost

CCV Design Process

The Control-Configured-Vehicle (CCV) design process includes active control system design in parallel with the other traditional disciplines.



Traditional Aircraft Design Process



Control-Configured-Vehicle Design Process

Project Objectives

1. Develop methods to assess control requirements for selected aircraft configurations without actually designing a control system.

2. Develop methods to rapidly determine aerodynamic parameters for controls assessment of high speed aircraft configurations.

3. Prepare these new methods for integration into a multidisciplinary design optimization environment.

Required Modeling Accuracy (XB-70)

The limits shown are the maximum variation allowed without causing a drop in the flying qualities level specified in five paragraphs of MIL-F-8785C.

	Mach 0.31 Sea Level		Mach 2.2 40,000 ft	
	min	max	min	max
$C_{L\alpha}$	-14%	971%	-23%	-
$C_{m\alpha}$	-30%	408%	-73%	33%
C_{mq}	-58%	895%	-28%	-
$C_{y\beta}$	-	-	-161%	-
$C_{l\beta}$	-689%	781%	-87%	-
C_{lp}	-	606%	-331%	111%
$C_{n\beta}$	-566%	865%	-104%	459%
C_{nr}	-361%	481%	-143%	-

Aerodynamic Estimation Accuracy

Stability Derivatives

Derivative	$C_{L\alpha}$	$C_{m\alpha}$	C_{mq}	$C_{Y\beta}$	$C_{n\beta}$	$C_{l\beta}$	C_{lp}	C_{nr}
Subsonic	◔	◔	◔	○	◕	◕	○	◔
Supersonic	○	◑	◑	○	○	●	◔	◑

Control Derivatives

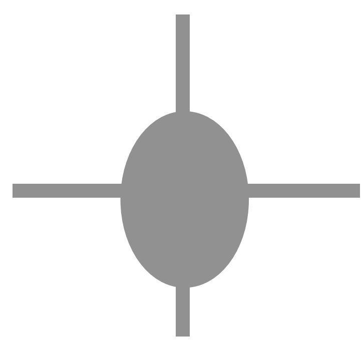
Derivative	$C_{L\delta f}$	$C_{m\delta f}$	$C_{n\delta f}$	$C_{l\delta f}$	$C_{L\delta c}$	$C_{m\delta c}$	$C_{Y\delta r}$	$C_{n\delta r}$	$C_{l\delta r}$
Subsonic	○	◔	◑	◔			◔	◔	◑
Supersonic	◔	◔	◕	●	○	○	○	○	◑

Very Good	Good	Fair	Poor	Not Useful
Error < 10%	10% < Error < 25%	25% < Error < 50%	50% < Error < 100%	100% < Error
○	◔	◑	◕	●

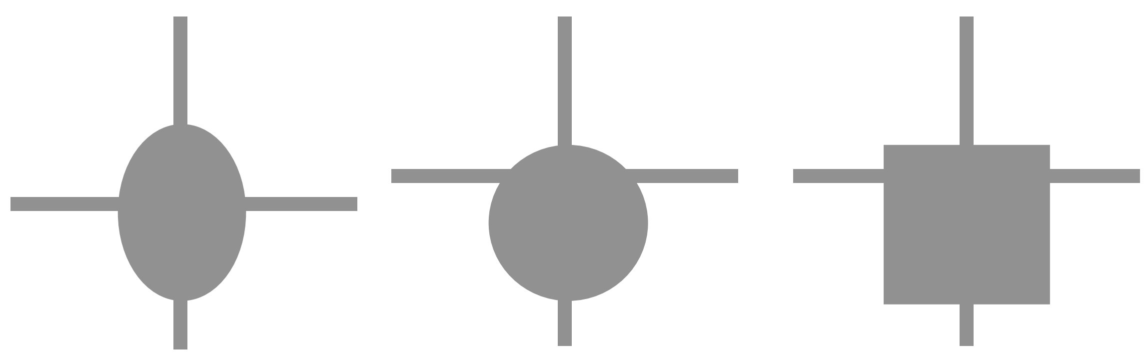
Improving Estimation Accuracy

Using Mathematica extends allowable configurations beyond DATCOM.

DATCOM Methods



New Methods



Estimation Software for Optimization

AEM (Aerodynamic Estimation Module) controls the process
started by Valery Razgonyaev, completed by Yannick Feder

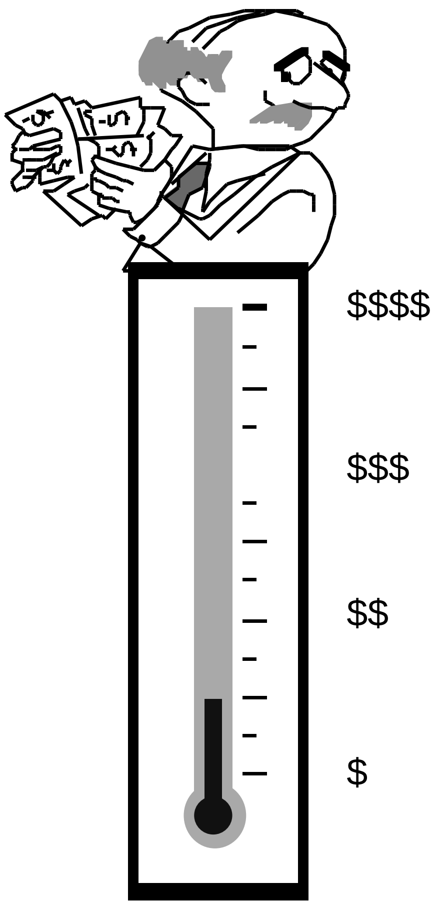
- Uses APAS for initial aero database
- Essentially uses APAS to provide fits to theoretical relations
  - in effect a response surface
- MATLAB environment used to execute optimization process
- Supporting Visualization package also developed
- Documented in VPI-AOE-240, Dec. 1996

"Controls" Optimization Function

To be compatible with existing optimization schemes, a controls cost function must be also be developed.

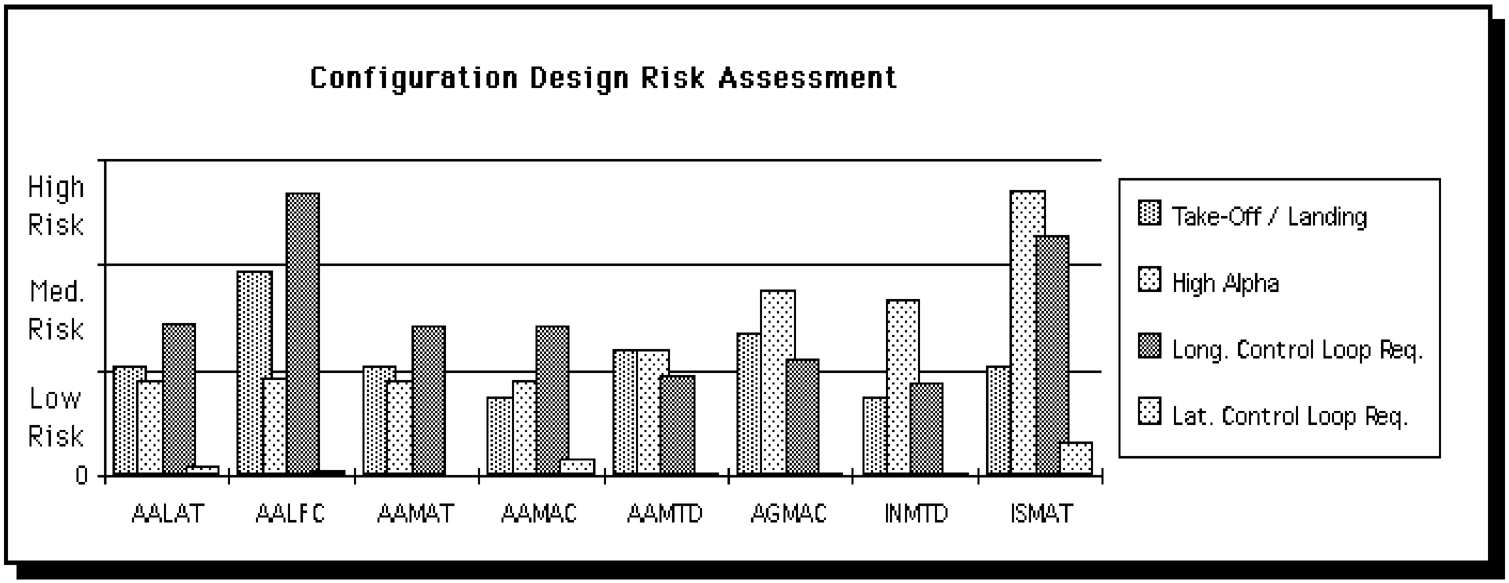
The controls cost function must be able to:

- penalize a configuration which cannot be controlled or requires a complicated control system
- reward a configuration which can be controlled easily/ cheaply
- yield some kind of continuous scale between reward and penalty



Control Design Risk Concept

Beaufrere introduced the concept of “control design risk” in the 1987.



High Risk: Cannot satisfy design specifications with new technology

Med. Risk: Can satisfy design specifciations with novel design approaches

Low Risk: Can satisfy design specifcations without novel design approaches

What should control risk measure?

Unlike many other disciplines involved in the aircraft design process, the flight controls discipline does not have an obvious figure-of-merit.

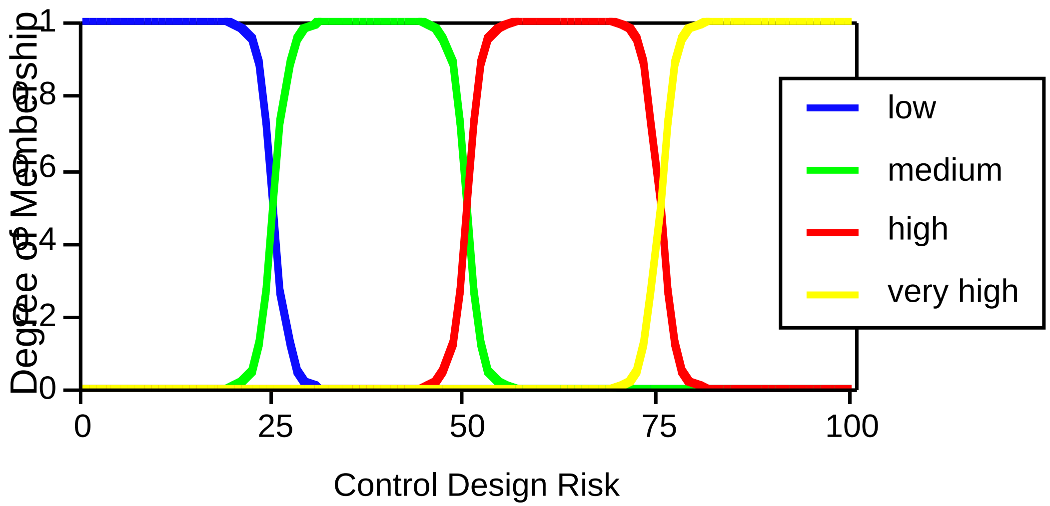
- Development or life-cycle cost?
- Component weight?
- Reliability or safety?
- Handling or ride qualities?
- Enhanced performance or agility?
- Stability margin?
- Model-following or tracking error?

Our approach has been to use the <u>complexity</u> of the required control system as a figure-of-merit for dynamic requirements.

Control System Design Risk

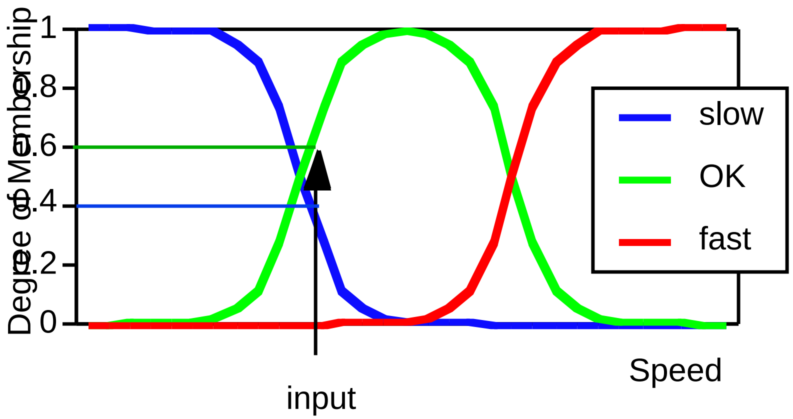
Control system complexity is categorized by the number of feedback loops and dynamic elements that are required.

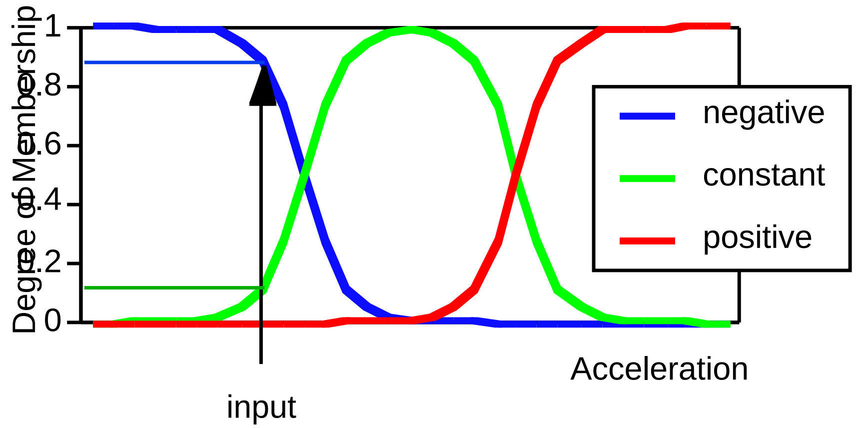
Complexity	Control System Type
Low	Bare airframe
Medium	Single-loop Stability Augmentation System (SAS)
High	Multiple-loop SAS
Very High	Proportional+Integral control



A control system design “risk” value is assigned by the fuzzy logic algorithm.

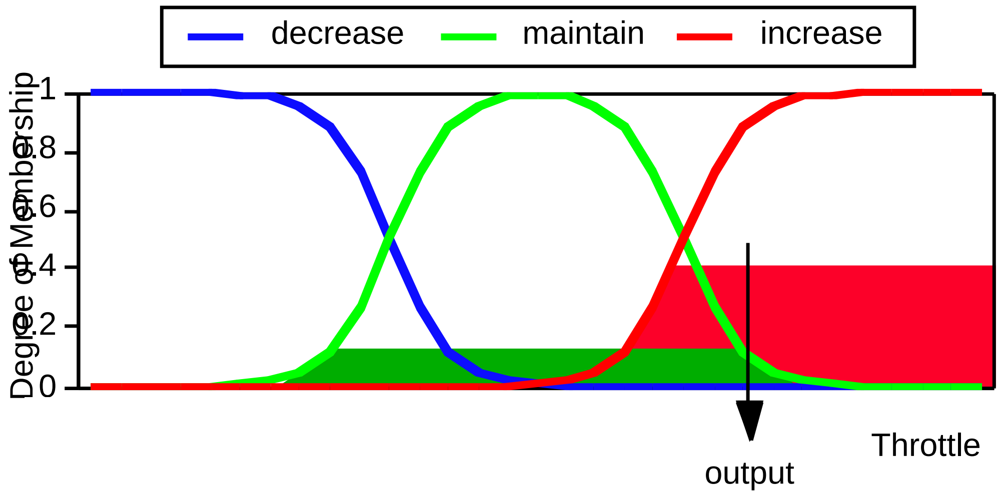
How Fuzzy Logic Works





Rule 1: IF speed is “slow” (0.4) AND acceleration is “negative” (0.9) THEN “increase” (0.4) throttle.

Rule 2: IF speed is “OK” (0.6) AND acceleration is “constant” (0.1) THEN “maintain” (0.1) throttle.



Translating Requirements into Rules

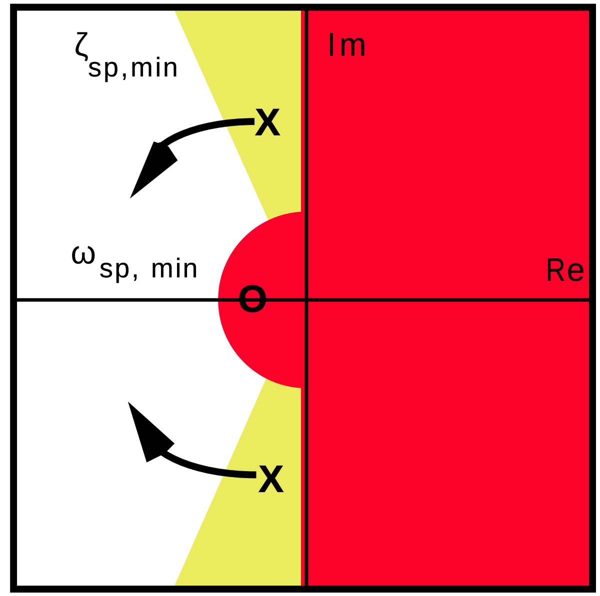
Rule #3: Pitch Damper

IF the short-period poles are "complex and stable"

AND $\omega_{sp}\,\tau_{\theta 2}$ is "within specification"

AND ζ_{sp} is "below specification"

THEN the control risk is "medium"



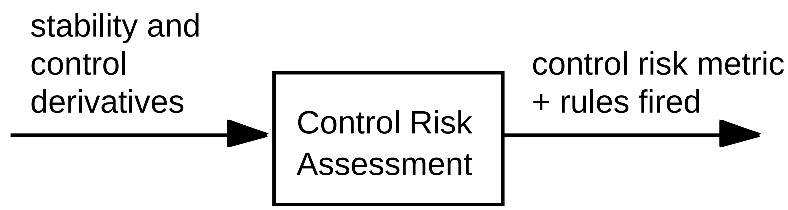
Rule #18: Take-off Rotation

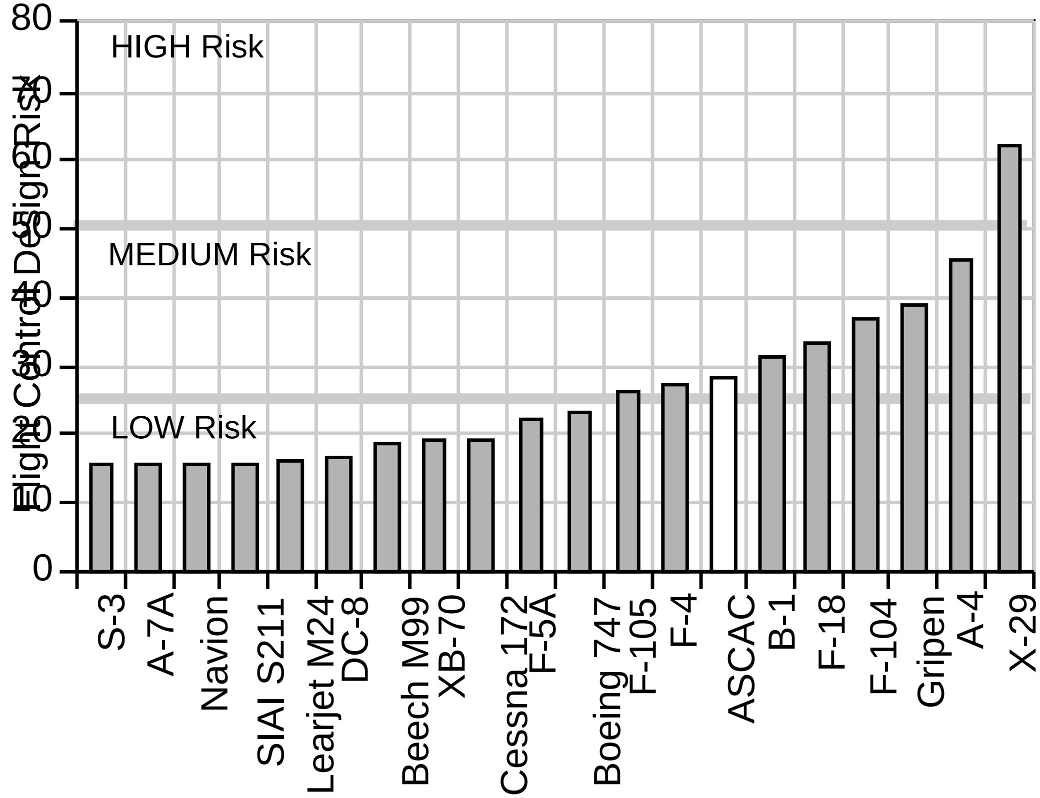
IF pitch acceleration at take-off is "below specification"

THEN the control risk is "very high"

Control Risk Comparison

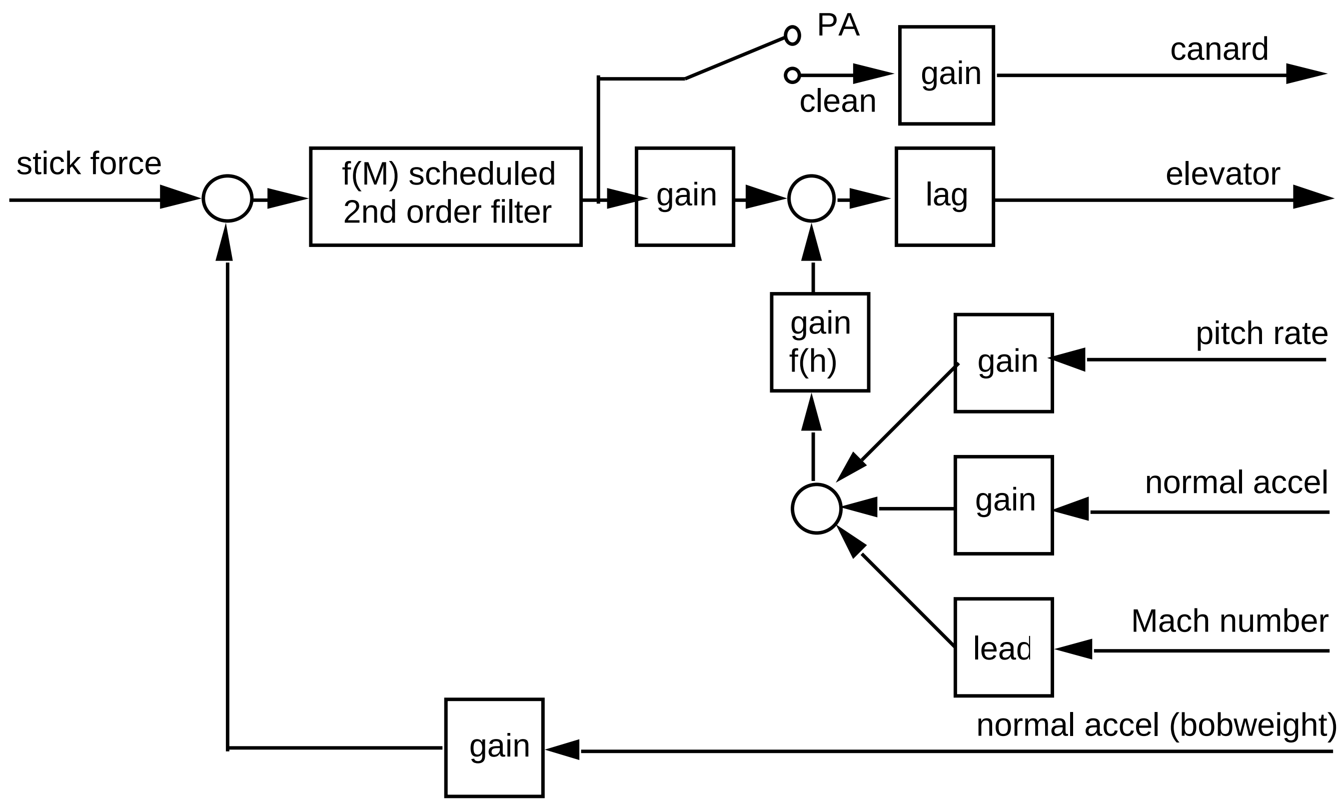
Existing aircraft control systems were studied to “calibrate” our risk metric.





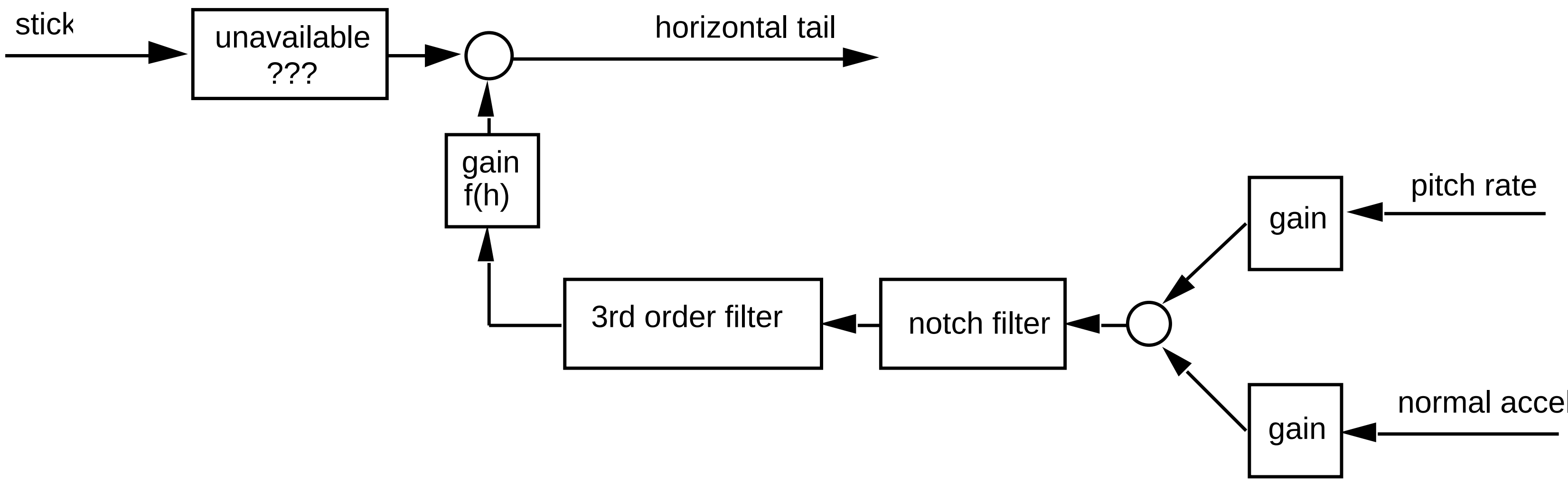
XB-70 Aircraft SAS

The XB-70 stability augmentation system (SAS) includes four measurement variables, two control output variables, and is third order.



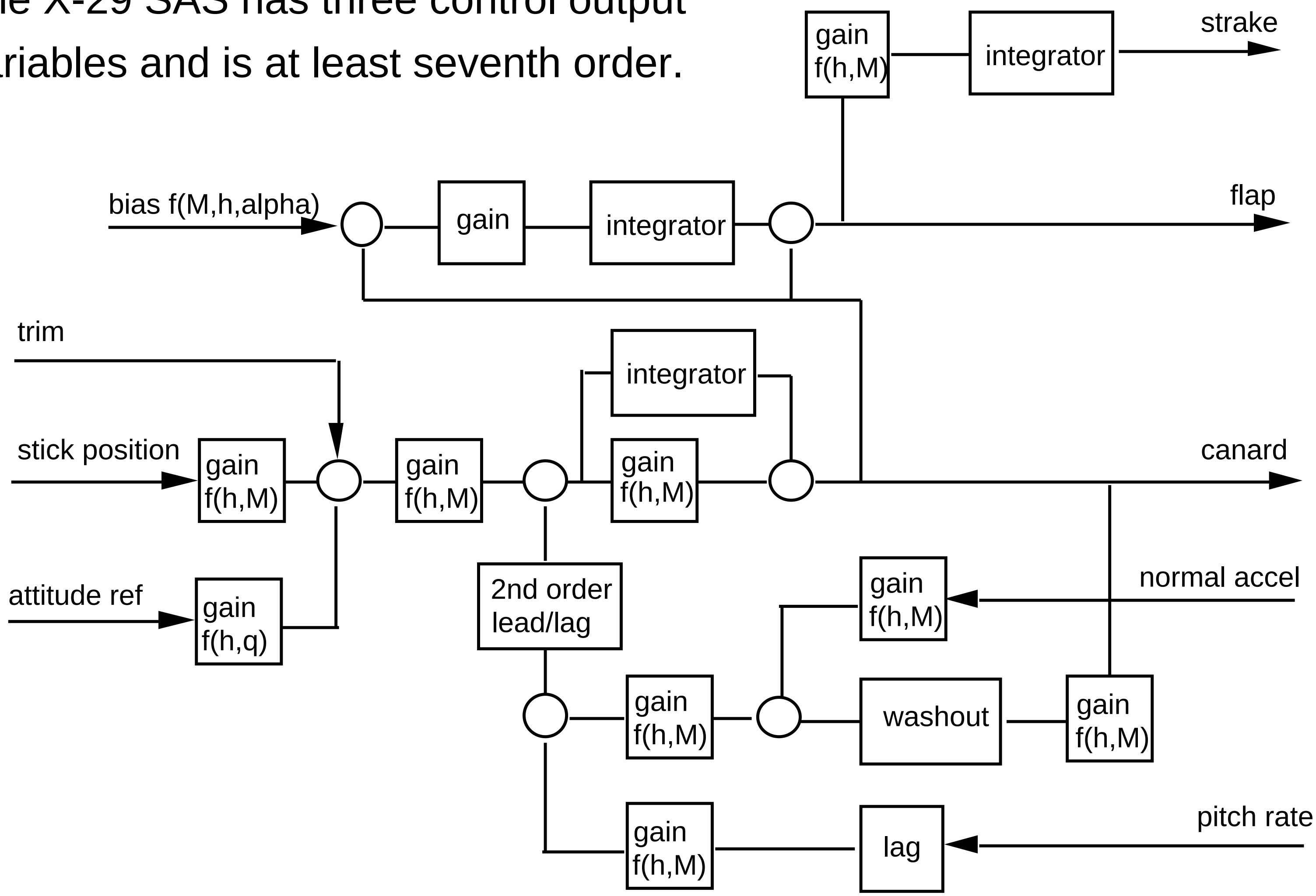
B-1 Aircraft SAS

Not counting its Structural Mode Control System (SMCS), the B-1 SAS includes two feedback measurements and is approximately fifth order.



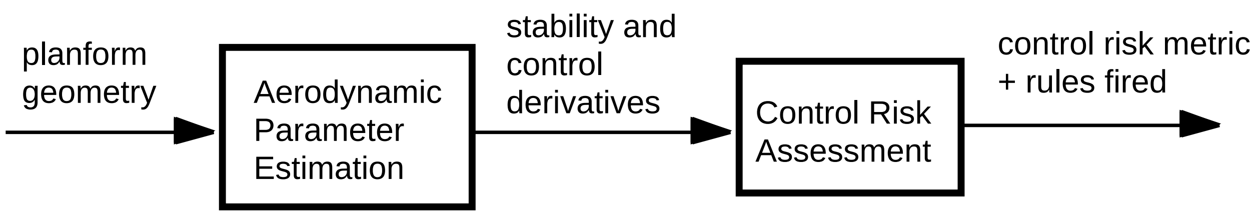
X-29 Aircraft SAS

The X-29 SAS has three control output variables and is at least seventh order.



Control Risk Sensitivity

By combining aerodynamic estimation and control risk assessment, an overall sensitivity can be obtained.



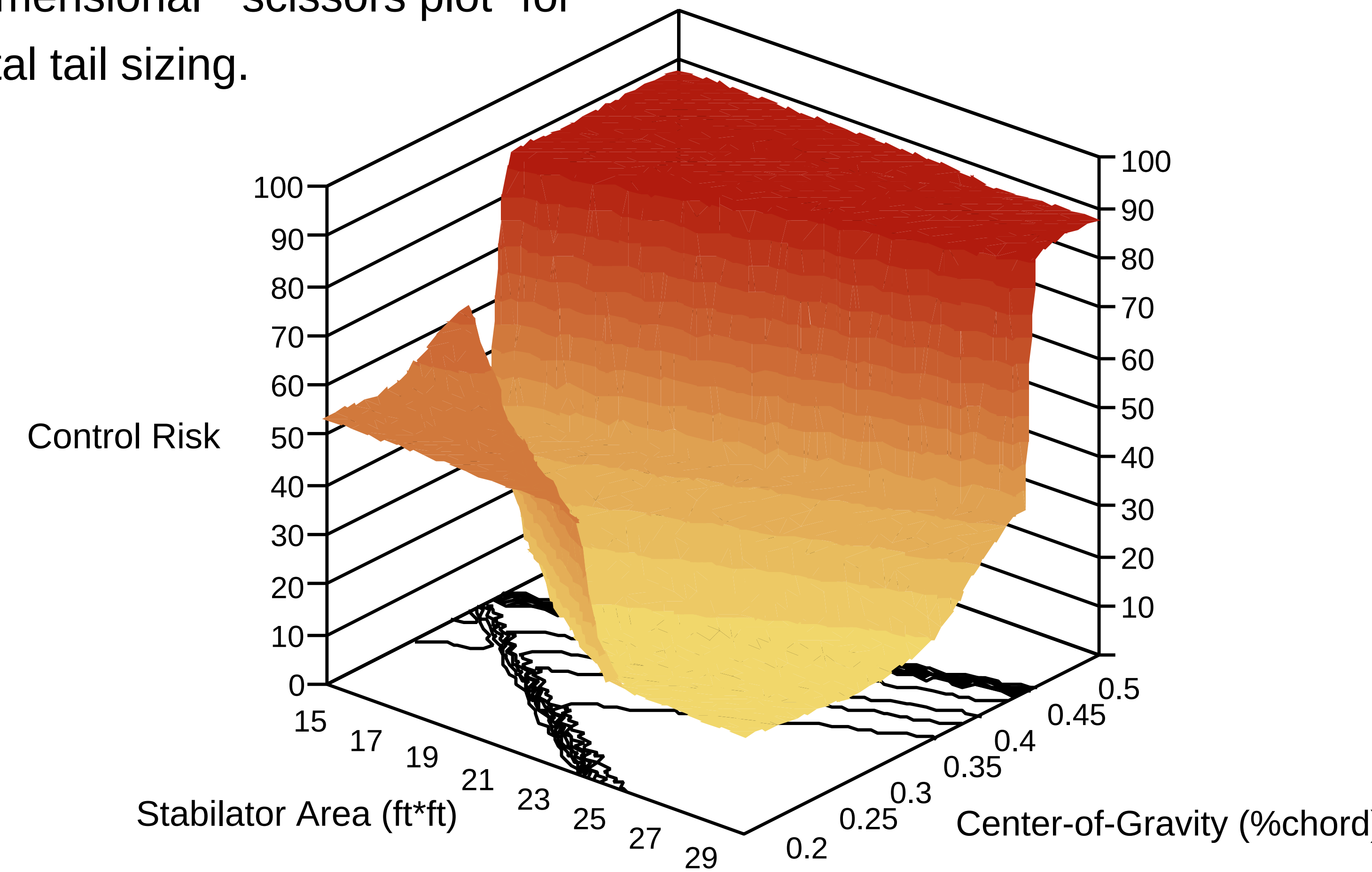
$$\boxed{\text{Sensitivity} = 100\,(p/R)\,(\partial R/\partial p)}$$

R = control risk
p = geometry parameter

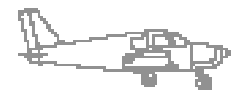
	Nominal	**Reduced Tail**
Weight	17.1	-74.6
Moment of Inertia	21.3	73.0
Chord	-78.6	-192.6
Distance from ref to Stabilator	-86.9	-143.8
Distance from ref to Wing	48.1	-30.0
Distance from ref to C.G.	-30.2	38.2
Wing Area	-14.0	72.1
Lift Curve Slope of Wing	-3.9	63.3
Stabilator Area	-24.2	-70.6
Downwash Coefficient	-26.5	11.3

A Control Risk Response Surface

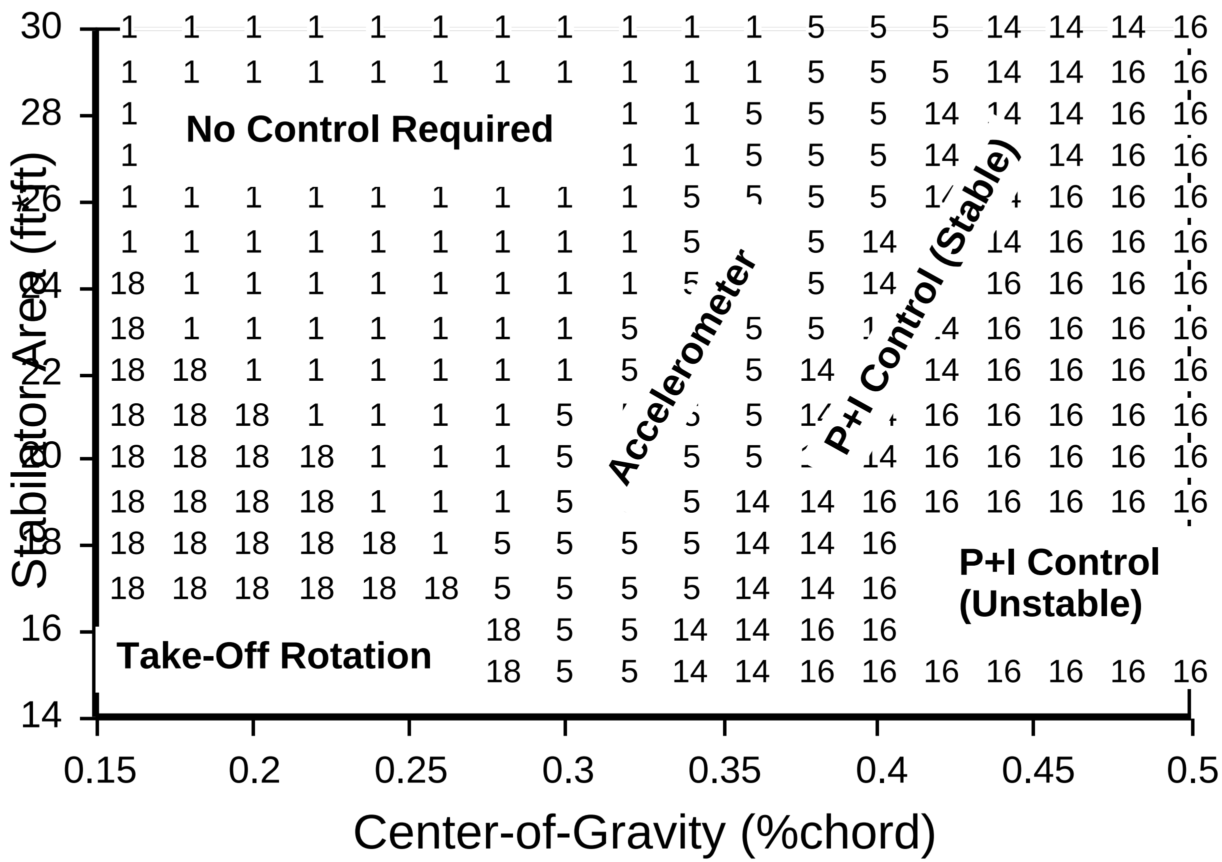
This control risk surface is actually a three-dimensional “scissors plot” for horizontal tail sizing.



Rule Strengths

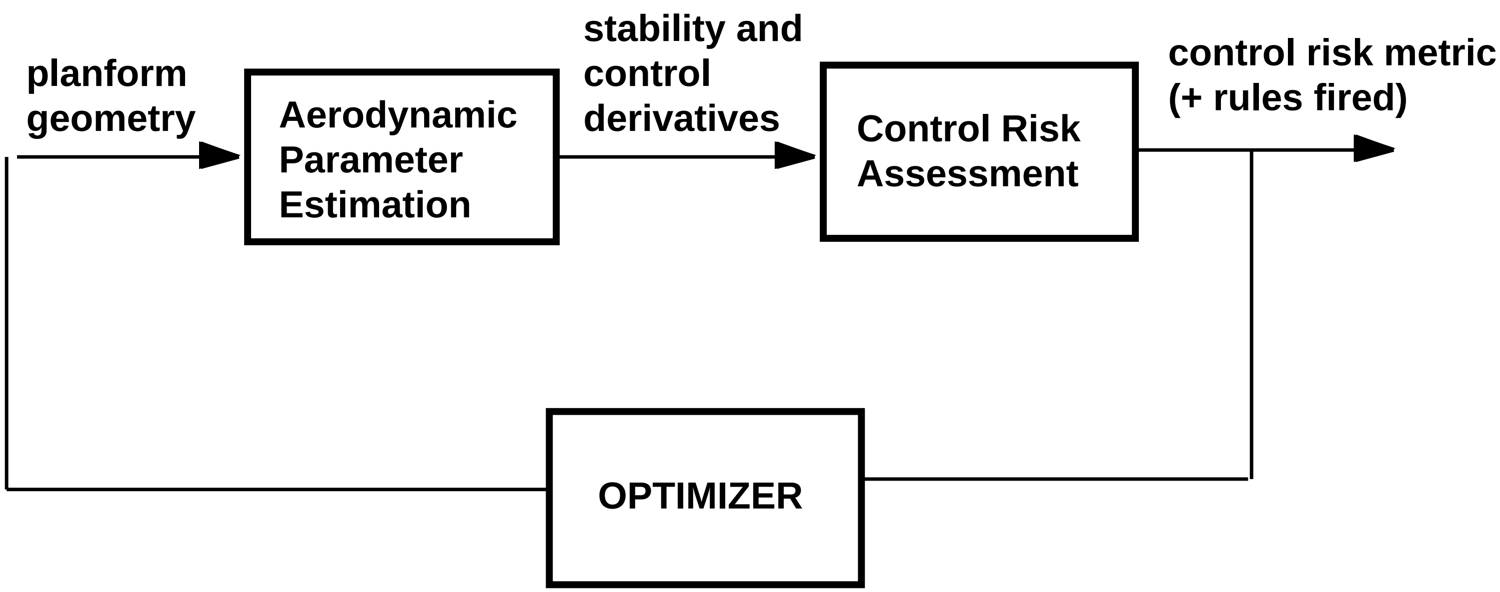


The highest rule strength determines the control system structure or constraint that is most influential.



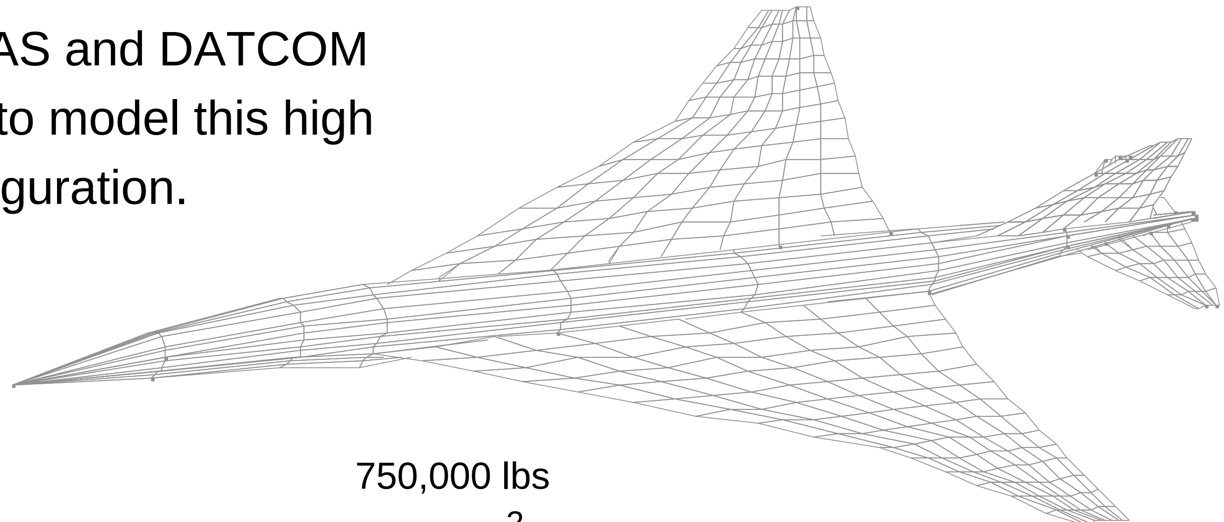
MDO Application

A multidisciplinary design optimization (MDO) problem is formed when information regarding control risk is used to modify the aircraft geometry.



McDonnell Douglas ASCAC

A combination of APAS and DATCOM extensions are used to model this high speed transport configuration.



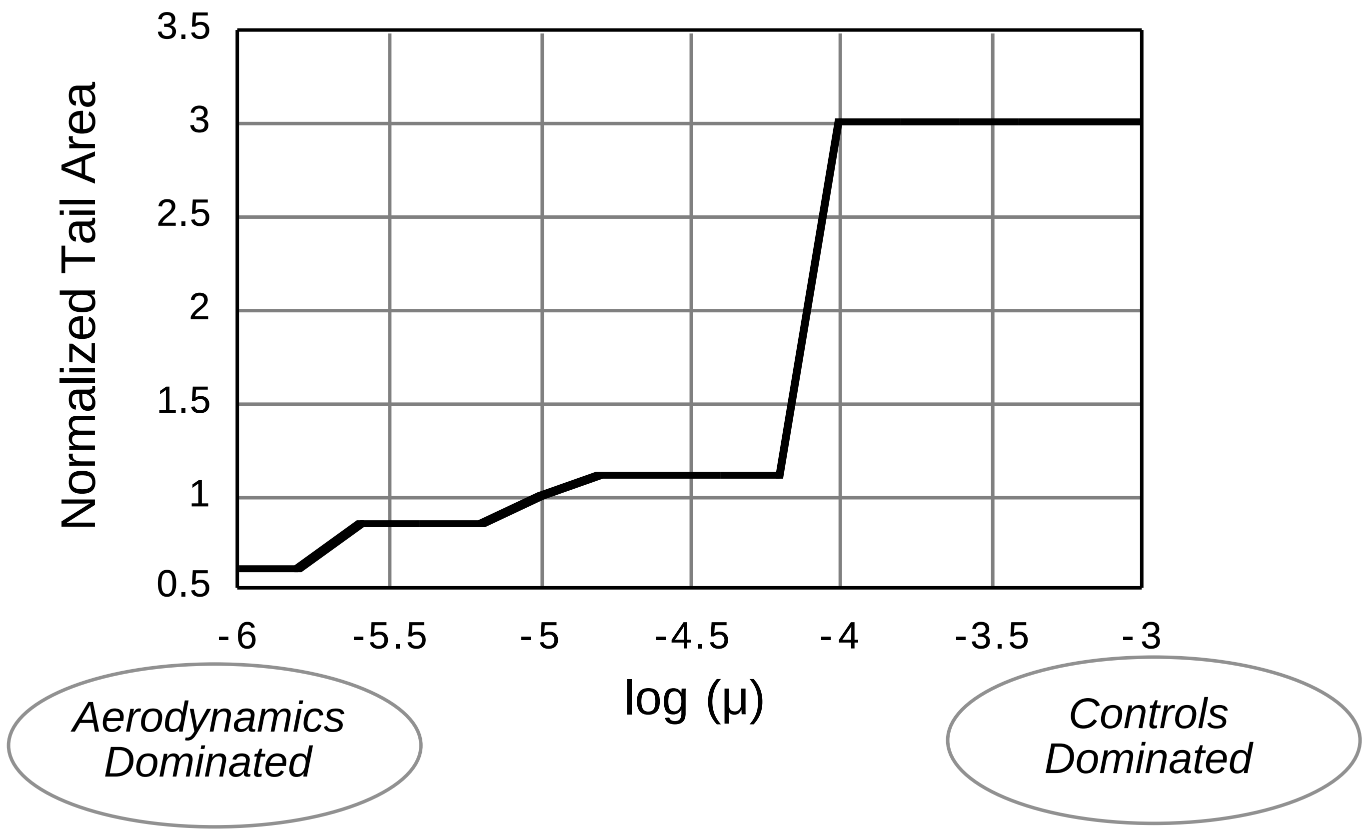
Aircraft Weight	750,000 lbs
Wing Reference Area	10,000 ft^2
Wing Span	135 ft
Wing Chord	65 ft
Refence Center-of-Gravity Position	184 ft
Horizontal Tail Reference Area	781 ft^2
Moment of Inertia (I_{xx})	1.8×10^7 slug ft^2
Moment of Inertia (I_{yy})	6.3×10^7 slug ft^2
Moment of Inertia (I_{zz})	8.0×10^7 slug ft^2

Design Problem Variables

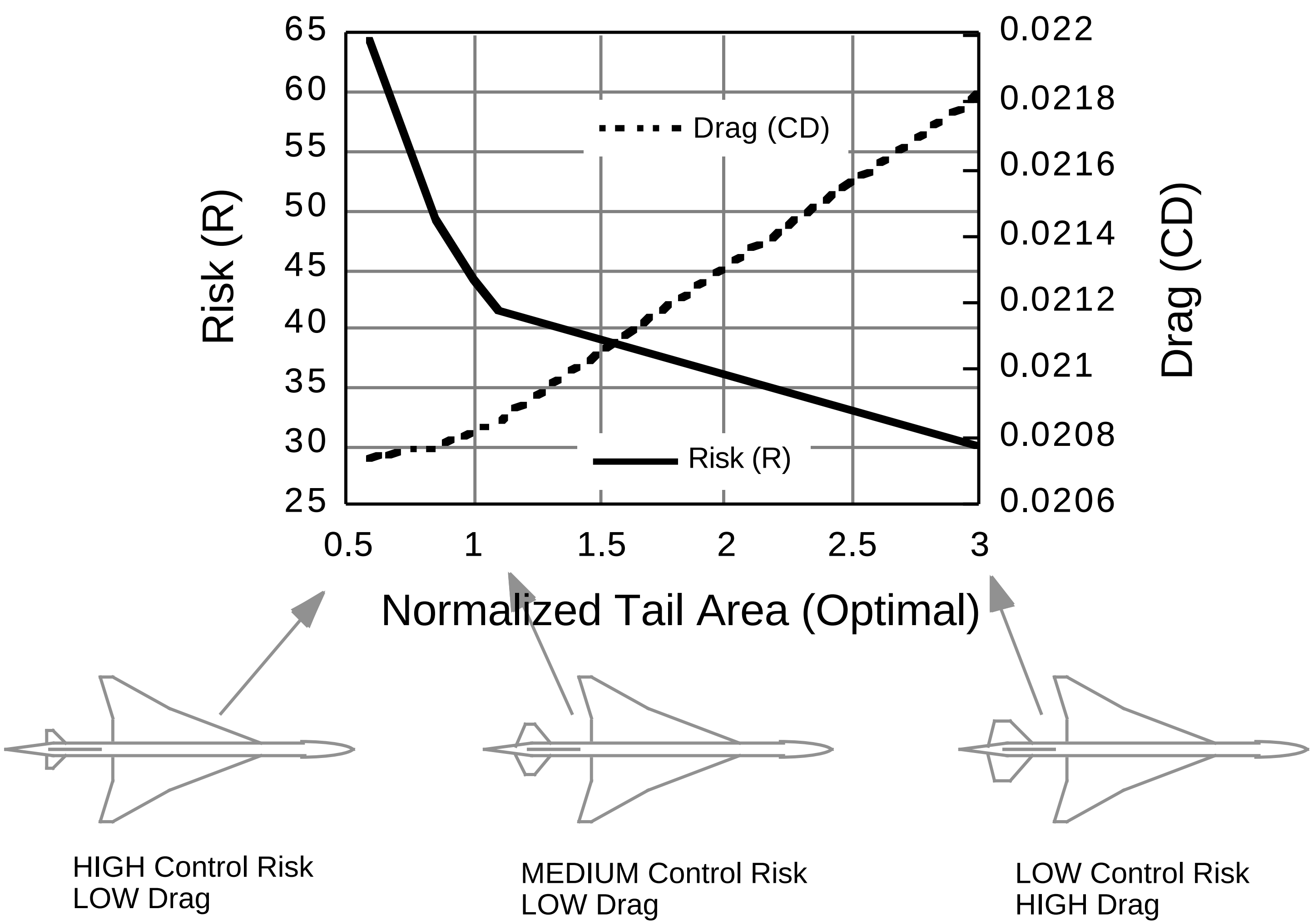
Optimization Problem Formulation

An optimization problem is formed using a weighted sum of control risk (R) and trimmed drag coefficient (C_D).

$$J = C_D + \mu R$$



Horizontal Tail Size Optimization



Significant Contributions

- New analytical expressions to model wing/body interference
- Aerodynamic estimation software to link APAS and MATLAB
- Accuracy comparisons between DATCOM, APAS, and vortex lattice
- New method for control design risk assessment using fuzzy logic
- Sensitivity calculations of control risk to variations in aircraft geometry
- Design studies of the XB-70, ASCAS, and a general aviation aircraft

Technology Transfer Efforts

A significant effort was made to reach industry and other groups.

- 4 conference papers (1 submitted to the Journal of Aircraft)
- 3 technical reports (2 NASA Contractor Reports in preparation)
- over 20 presentations, meetings or contacts
  - NASA LaRC
  - Joint Strike Fighter Program Office
  - Wright Laboratory
  - Multidisciplinary Analysis and Design Advisory Board
  - Naval Strike Aviation Team
  - SAE Control and Guidance Systems Committee
  - Boeing Commerical Aircraft
  - Beech/Raytheon
  - North American Rockwell

What did we learn?

- Difficulty with the concept of control risk
- Difficulty with the fact that no control system design is produced
- Unwillingness to share proprietary data
- Modeling programs used in optimization are not ready for large-scale configuration variations